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PHOTOLUMINESCENCE FROM Er-IMPLANTED 4H AND 6H-SiC

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ABSTRACT

Erbium (Er) ions were implanted into 4H and 6H silicon carbide (SiC). The temperature-dependent photoluminescence (PL) and PL lifetime were characterized. The optimum annealing temperature for SiC : Er were 1600 ℃. PL intensity decreased at 1700 ℃, and the bandedge luminescence changed in relation to the luminescence of Er^{3+}. Thermal quenching of the luminescence of Er^{3+} was suppressed by using SiC with a wide band gap as a host material. The Er^{3+}-PL was observed at room temperature (RT). We monitored the auger effect that is believed to be the main cause of the thermal quenching process and concluded that, in the temperature range 15 K to 70 K, the thermal quenching process has a close relation to nonradiative recombination from the first excited state ($^4I_{13/2}$) to the ground state ($^4I_{15/2}$) of Er^{3+}.

INTRODUCTION

An Erbium (Er)-doped semiconductor is a potentially useful material for light-emitting devices in optical communication systems, since the intra-4f-shell transitions of Er ions cause sharp and temperature-stable luminescence in various host materials [1], [2] at 1.54 μm, which corresponds to the minimum absorption of silica-based optical fibers.

Photoluminescence (PL) from Er^{3+} in Er-doped narrow band gap semiconductors [e.g., silicon (Si)] has been reported [3]-[7], but the PL is weak and difficult to observe at room temperature (RT). One of the reasons for difficulties in obtaining the Er^{3+}-PL at RT is the low level of probability of Er excitation via recombination of free carriers, as has been theoretically explained by *Needles* et al. [8].

However, an increase of Er^{3+} luminescence could be realized by the introduction of light impurities, such as C, N, and O, and by using a wide band-gap material as a host material. The influence of the introduction of light elements on Er^{3+} luminescence in Si: Er and GaP : Er was studied by us using standard PL and photoluminescence excitation (PLE) techniques [1], [2]. We proposed that light

elements form complexes with the Er atoms and an efficient excitation of Er^{3+} occurs via a recombination of the electron-hole (e-h) pair, where one of the carriers located at Er-complex-related deep levels in the forbidden-gap [1], [2].

Silicon carbide (SiC), anticipated to be a useful material for high-temperature applications, is a very useful host material because it has a wide band gap and improves the luminescence properties of the Er^{3+} ions [9]-[12]. The aim of this work is, therefore, to investigate the effect of a wide band-gap host material on Er^{3+} luminescence. We use 4H and 6H-SiC as host materials.

EXPERIMENT

The wafers used in this work, which are single crystal SiC wafer produced by Lely method, (obtained from *Cree Research, Inc.*) were nitrogen doped hexagonal polytypes 4H and 6H-SiC. The orientation of the wafer flat is $\langle 11\bar{2}0 \rangle$ direction. The n-type wafer is uniformly predoped with nitrogen. The polished side, terminated with Si, is used for the implantation. Er implantation was carried out at 2 MeV with doses of $1\times10^{14}cm^{-2}$ at RT. The projected range (R_p) and straggling (ΔR_p) for the Er implant profile were calculated by TRIM to be 505.1 and 78.8 nm, respectively. In order to be compared with SiC:Er, Ytterbium (Yb) ions were implanted into 4H-SiC. Yb implantation was carried out at 2MeV with doses of $1\times10^{13}cm^{-2}$ at RT. The projected range for the implanted Yb ions was almost the same as that for the Er ions. We held their samples on carbon plate using a quartz sample holder in the rapid thermal annealing apparatus (RTA). The samples were annealed at temperatures ranging from 1400 to 1700 ℃ for 40 min in a pure argon (Ar) atmosphere (purity:99.999%) using a halogen flash lamp. The heating and cooling rates were 7.1 ℃/s. Before annealing, the apparatus was pumped down to a base pressure of 5×10^{-6} Torr before Ar gas was fed into the vacuum chamber. Samples were placed into a closed-cycle helium gas cryostat and were held at temperatures ranging from 15 to 300 K. PL was excited using the 325-nm line of a mechanically chopped helium-cadmium (He-Cd) laser. The penetration depth of the He-Cd laser (325 nm) for SiC was approximately 520 nm. This depth value was calculated from published absorption coefficient data [13]. The PL spectrum was recorded in a standard lock-in configuration using a 1-m double monochromator, and a InGaAs photomulutiplier (*Hamamatsu Photonics R5509-72*).

RESULT and DISCUSSION

Figure.1 shows greater detail of the evolution of the Er spectra in 4H-SiC:Er as warming up the sample from 15 K to R.T.. Several peaks were observed at around 1.5μm and the dominant peak is located at 1534.0 nm. For the hexagonal polytypes 4H-SiC and 6H-SiC, the 15 K spectrum is very similar with a dominant line at 1534.0 nm and 12 peaks or other small peaks. In order to optimize the luminescence intensity of Er^{3+}, we investigated its annealing temperature dependence. As to the Er-related PL spectra of SiC:Er for different annealing temperatures, from 1400 ℃ to 1600 ℃, the shape of Er-related spectra became sharp and the PL intensities increased on increasing the annealing temperature.

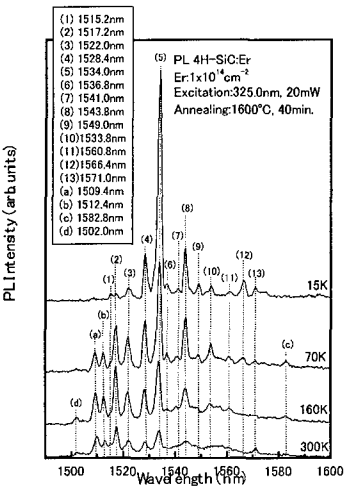

Fig.1 *The temperature dependence of the Er^{3+}-related PL spectra of 4H-SiC:Er*

Both PL intensities in the sample annealed at 1700 ℃ decreased as compared with those of the sample annealed at 1600 ℃. It has been reported that a layer of carbon (C) is formed on the sample surface by the sublimation of Si atoms at or above 1500 ℃[14], [15]. At 15 K there is 13 peaks visible at higher energy than the peak(1) at 1515.2 nm. 2 peaks [(a), (b)] were seen at 40K, and peak(d) was seen at 160K. After all, at 300 K we have sprouted 3 peaks at higher energies of which were actually larger than the original peak(1) at 1515.2 nm. Er^{3+}-related PL was observed at R.T. by using SiC with a wide band gap as a host material. These data strongly suggest that at each temperature we are seeing transitions from excited states of the crystal field spin orbit levels of Er^{3+}, $^4I_{13/2} \rightarrow {}^4I_{15/2}$.

Figure.2 shows the temperature dependence of the Er^{3+}-related PL intensity at the dominant peak(5) of wavelength 1534.0 nm in SiC:Er. In *Fig.2* the experimental data were plotted along with the theoretical (solid line) based on eq.1 [16] using the parameters (C_1, C_2, C_3, E_1, E_2, E_3) shown in *Table 1.*

$$I(T)=I_o/(1+C_1\exp(-E_1/kT)+C_2\exp(-E_2/kT)+C_3(-E_3/kT)) \qquad (1)$$

15~70K	C_1	E_1(meV)
	4	8
70~160K	C_2	E_2(meV)
	9.5	40
160~300K	C_3	E_3(meV)
	100	100

Table 1. *Fitting parameter for dominant peak of SiC:Er used in eq.1*

In the above equation I_o is the intensity at which the electron emission from the Er^{3+}-related trap can be neglected. Hence it corresponds to the intensity at a very low temperature. T is temperature, E_1 and E_2 are the activation energies, and k is the Boltzmann constant C_1, C_2 and C_3 are the coupling coefficients at E_1, E_2 and E_3 respectively. The experimental data well fitted by eq(1). Peak(3), (4) and (12) were not able to do the fitting because the luminescence strength increased with the rise of measurement temperature. *Table1* shows the activation energy (E_1, E_2 and E_3) and fitting parameter (C_1, C_2 and C_3).

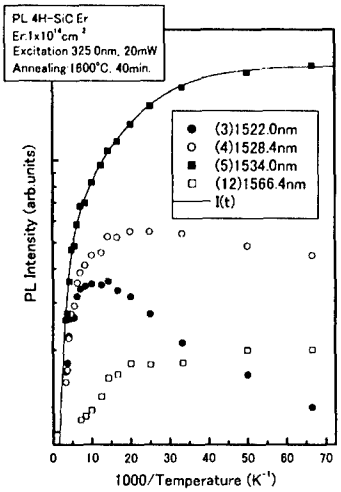

Fig.2 *The temperature dependence of the Er^{3+}-related PL intensity at each peak of 4H-SiC:Er with fitting*

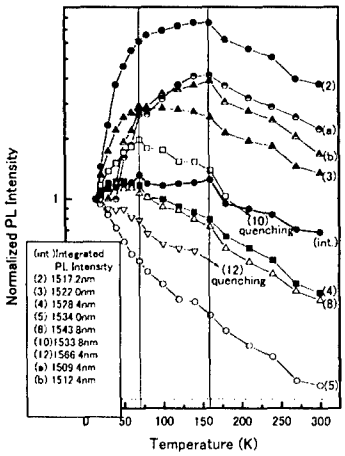

Fig.3 *The temperature dependence of the Er^{3+}-related PL intensity at each peak of 4H-SiC:Er*

Figure3 shows dominant peak(5) has different behavior for temperature dependence compared with other peak. Therefore it is clear that there are at least two thermal quenching processes. We can't say for certain whether Er atoms occupy the Si or C sites. It may be that Er atoms occupy

interstitial sites. However, we have already investigated the mechanism of the luminescence of Er^{3+} in Si, which was due to the presence of Er-C complexes [2]. On these grounds, we conclude that Er forms at least two Er-C complex centers with C which contribute to the luminescence of Er^{3+} in SiC:Er.

Figure.4 shows the temperature dependence of the Yb^{3+}-related PL intensity at the dominant peak(3) of wavelength 999.8 nm in SiC:Yb. In the range 940.0 nm-1040.0 nm, 5 peaks correspond in location to the luminescence levels of the Yb ion in the 4H-SiC crystal. Yb is a typical uncontrollable impurity in SiC.

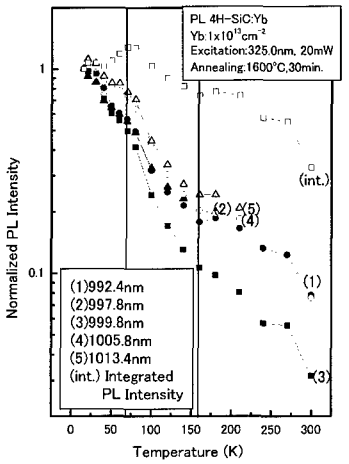

Fig.4 The temperature dependence of the Yb^{3+}-related PL intensity at each peak of 4H-SiC:Yb

Both Er and Yb temperature dependence (shown in *Fig.3* and *Fig.4*) are very similar characteristics. The similar feature of the observed PL of Er and Yb were the unusual temperature dependence of its intensity although Er^{3+}-related PL intensity increased with rising temperature. As the temperature increases beginning with 15K, both PL intensity of Er and Yb rapidly increase and reach a maximum value at 70 K. On the other hand, as the temperature increased beginning with 70 K, both PL intensity of Er and Yb rapidly decreased. By investigating these results, it is suggested that at more than at 70 K, electrons and excitons can't be capture by one level and the position of the level is in 6 meV under the conduction band.

Figure.5 shows the luminescence decay curve of the Er^{3+}-related PL intensity at the peak of 1534.0 nm in SiC:Er. Biexponential decay times τ was estimated via component stripping and are shown in *Fig.5*. We estimated the radiative decay time(τ_r) and nonradiative decay time (τ_{nr}) using eq.2, eq.3 and the value of measured lifetime τ in *Fig.5*. The value of τ in the luminescence decay curve, τ is shown in *Figure6*.

$$1/\tau(T)=1/\tau_r(T)+1/\tau_{nr}(T) \qquad (2)$$

$$I(T)=\eta(T)*I_0 \qquad (3)$$

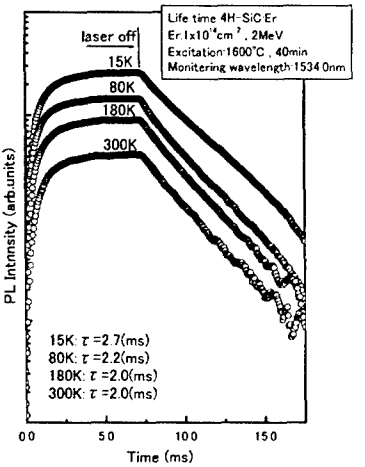

Fig.5 The temperature dependence of the luminescence curve of the Er^{3+}-related PL intensity at the peak of 1534.0 nm

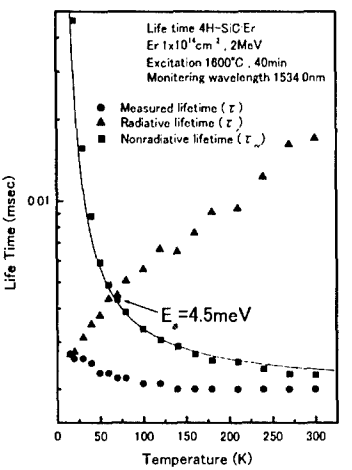

Fig.6 The temperature dependence of the τ_r, τ_{nr} and τ

In *Figure.6* the experiment data were plotted along with the theoretical (solid line) based on eq.4 [17] using the parameter (E_a).

$$\tau_{nr}=(1/N_{BV}\sigma)*\exp(E_a/kT) \qquad (4)$$

As a result, E_a=4.5meV. In the above equation, N_B is the density of nonradiative center, v is the thermal velocity of the carrier, σ is the capture cross section of nonradiative centers, E_a is the activation energy. T is temperature and k is the *Bolzmann* constant. The values of E_I (=8meV) approximately coincided with the value of E_a. Therefore we conclude that the thermal quenching process, which occurs in the low-temperature range (15K < T < 70K), reflects the nonradiative recombination in the transition from the first excited state ($^4I_{13/2}$) to the ground state ($^4I_{15/2}$) of Er.

To summarize we showed the proposed mechanism and scheme of these energy levels in *Figure 7.*

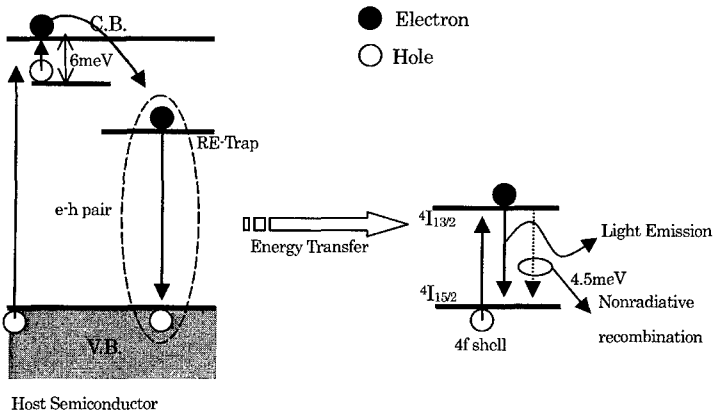

Fig.7 Possible scheme of the energy levels and mechanisms of energy transfer in the hexagonal SiC

CONCLUSION

From above results, we can conclude as follows.

(1) It was found that the optimum annealing temperature and time for 4H and 6H-SiC were 1600 ℃, 40 min., respectively.

(2) By investigating the temperature dependence of the Er^{3+}-related PL intensity, we found that thermal quenching of the luminescence of Er^{3+} was suppressed by using SiC, instead of Si, as a host material, and that Er forms at least two Er-C complex centers with C which contribute to the luminescence of Er^{3+} in SiC:Er. Er^{3+}-related PL was observed at R.T. by using hexagonal polytypes 4H and 6H-SiC with a wide band gap as a host material.

(3) By investigating the temperature dependence of the Er^{3+} and Yb^{3+}-related PL intensities we consider that at more than at 70K, electrons and excitons can't be capture by one level. It is suggested that the position of the level is in 6meV under the conduction band.

(4) The thermal quenching process in the low-temperature range from 15K to 70K shows has a close relation to nonradiative recombination in the transition from the first excited state ($^4I_{13/2}$) to the ground state ($^4I_{15/2}$) of Er^{3+}.

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